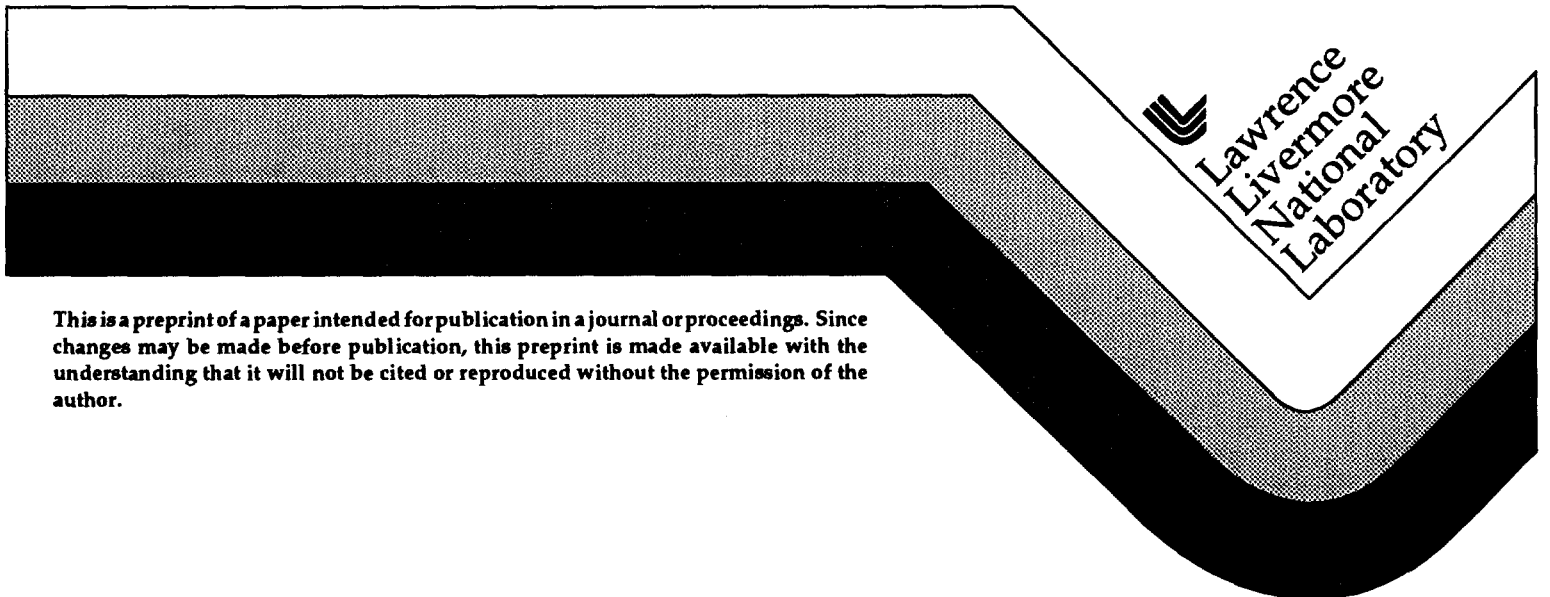


1-Watt Composite-Slab Er:YAG Laser

R. H. Page, R. A. Bartels, R. J. Beach,
S. B. Sutton, L. H. Furu, and J. E. LaSala

This paper was prepared for submittal to the
12th Topical Meeting on Advanced Solid-State Lasers
Orlando, Florida
January 27-29, 1997

February 13, 1997



This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

1-watt composite-slab Er:YAG laser

Ralph H. Page, Randy A. Bartels, Raymond J. Beach,
Steven B. Sutton, Larry H. Furu, and John E. LaSala
*Lawrence Livermore National Laboratory,
Mailcode L-441, P.O. Box 808, Livermore CA 94551*

Abstract

A diode-side-pumped discrete-optic Er³⁺:YAG laser employs pump-light coupling through a sapphire plate diffusion-bonded to the laser slab, removing heat directly at the pump face of the slab instead of requiring conduction through to its far side. This lowers the temperature in the gain region and gives reduced thermal lensing, which produces exceptional beam quality ($M^2 \sim 1.3$) at output powers ~ 0.3 Watt. Powers above 1 Watt have been demonstrated with peak slope efficiencies $\sim 20\%$. The novel architecture is also applicable to other side-pumped lasers.

Keywords

Infrared and far-infrared lasers, Optical resonators, Rare earth and transition metal solid state lasers, Thermal lensing

The Er³⁺ laser has recently been investigated rather intensively with the goal of improving its efficiency[1 - 3] and understanding the complex level kinetics[3,4] that allow quasi-CW operation in a variety of oxide[5] and fluoride[6] hosts. Near-Watt-level operation has been demonstrated, mainly with end-pumped[1 - 3, 5] and monolithic[1, 5] designs that inherently afford excellent spatial overlap between the tightly-focused pump and resonated beams. Unfortunately, limited diode pump brightness hampers scaling to higher power levels in such schemes.

To sidestep this diode brightness limitation, we developed a side-pumped laser[7] (based on a design introduced by Bernard[8]) compatible with LLNL-developed high-brightness laser diode array packages. Characterization of this laser showed that thermal focusing in the laser slab limited the obtainable average power and

beam quality. Further experiments showed that a substantial increase in laser efficiency could be achieved by lowering the temperature of the Er:YAG crystal.

Evidently much can be gained with improved cooling techniques that (a) reduce the temperature in the gain region and (b) reduce thermal lensing, which is especially problematic in a laser which is side-pumped on only one side, giving a very astigmatic thermal lens. Our new "composite" design (Figure 1) has the Er:YAG crystal bonded to a sapphire plate through which the pump light is transmitted, providing both of these improvements. First, the heat removal takes place at the crystal pump face, shortening the conduction path (compared with the ~ 2 mm dimension in the original design) and reducing the effective thermal impedance. The region of greatest heating directly adjoins the sapphire heat sink. This, the

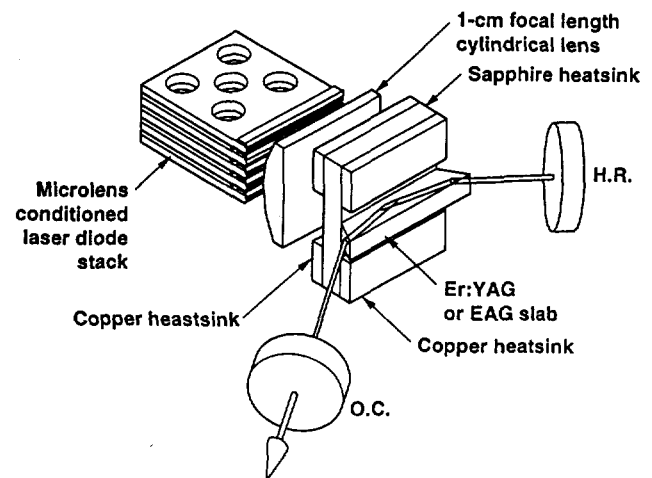


Figure 1. Composite-design diode-pumped Er:YAG laser with "TIR-bounce" beam propagation. The Er:YAG slab is diffusion-bonded to a sapphire plate that removes heat directly at the pump face, reducing the gain-region temperature and reducing thermal lensing.

coldest spot in the crystal, is also the region of peak amplification. Second, removing the heat from the pump face (and from no other region) largely eliminates heat conduction from the front to the back of the crystal, creating a zone free of temperature gradients. This gradient-free zone (see below) largely equalizes the optical path length $OPL \equiv \int n \, ds$ across the aperture of the resonated beam, substantially reducing thermal lensing.

The composite-sample design (Fig. 1) largely resembles the original design (Ref. 7,) since the pump diode array and resonator optics are similar. The pump array is larger (5 bars instead of 4) and less tightly focused, giving a spot 350 μm high and 10 mm long, and the overall pump delivery efficiency is only ~63% because of clipping and non-AR-coated optics. Peak pump power delivered to the crystal is estimated to be 156 Watt. Heat is removed from the 2 mm-thick sapphire plate with water-cooled copper heat sinks containing apertures for pump light delivery.

Two different laser samples[9] were used-- $\text{Er}_{1.5}\text{Y}_{1.5}\text{Al}_5\text{O}_{12}$ ("Er:YAG") and $\text{Er}_3\text{Al}_5\text{O}_{12}$ ("EAG.") Effective pump absorption coefficients were $\sim 20 \, \text{cm}^{-1}$ in each case. Brewster-cut faces resulted in sample dimensions of 2mm x 2mm x 10mm x 11.4 mm. The polished laser slabs were "diffusion-bonded" to 10 x 10 x 2 mm sapphire plates in a manner preserving a high-optical-quality interface. Four primary considerations led to selection of sapphire for the plate material: (1) high thermal conductivity (28 W/m \cdot K, to be compared with 5 W/m \cdot K for Er:YAG,) (2) high transparency at the 2.94 μm laser and 965 nm diode pump wavelengths, (3) refractive index difference sufficient for TIR at reasonable angles of incidence ($\Delta n = 0.06$ at 3 μm for a 16° maximum grazing angle,) and (4) ability to bond to Er:YAG. Diffusion bonding of Er:YAG to sapphire,[10] currently developmental, gave bonds best along the midlines of the laser crystals.

Calculated temperature profiles indicate a $\sim 50 \, ^\circ\text{C}$ smaller temperature rise in the pump face/ TIR bounce region for the composite design than in the original design. Whereas the original design shows a steadily-declining temperature due to heat conduction from the front to the back of the crystal, the composite design has a nearly gradient-free region at the back of the crystal.

The utility of the gradient-free zone is illustrated in Figure 2, a conceptual view of the isotherms in a slice through the mid-plane of the laser crystal (assuming uniform heat deposition per unit length and a pump penetration depth short compared with the crystal depth.) The horizontal tilt and focus imposed on a beam entering the crystal at a depth z_0 are respectively proportional to $\partial OPL / \partial z_0$ and $\partial^2 OPL / \partial z_0^2$, where $OPL \equiv \int n \, ds$. With beam entry and exit via the gradient-free region, these derivatives (and higher-order z-axis derivatives) are

identically zero, eliminating pump-light-induced horizontal beam steering and focusing.

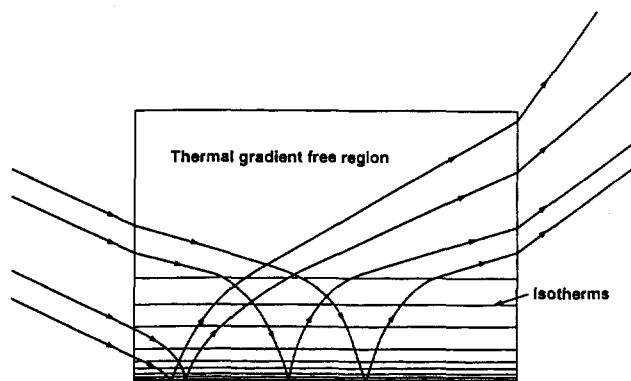


Figure 2. Conceptual view of isotherms in a slice through the laser slab's midplane, showing that heat removal at the pump face creates a gradient-free region deep in the crystal. Laser-beam entry and exit via this region eliminates horizontal-axis lensing and beam steering.

Thermal lensing measurements were performed on the original and composite laser samples, with extracavity 633 nm probing (along the path taken by the 2.94 μm beam during laser operation) of the laser crystals experiencing varying diode-array pump powers. As expected, the inverse focal length scaled linearly with pump power. Whereas the focal power $(1/f)/P_{\text{pump}}$ in the horizontal plane of the original design was $4.9 \times 10^{-2} \, \text{cm}^{-1}/\text{W}$, the composite design had a focal power of $0.68 \times 10^{-2} \, \text{cm}^{-1}/\text{W}$, indicating a factor of 7.2 reduction in thermal lensing. The vertical focal power dropped from $3.5 \times 10^{-2} \, \text{cm}^{-1}/\text{W}$ in the original design to $0.81 \times 10^{-2} \, \text{cm}^{-1}/\text{W}$ in the composite design, a factor of 4.2 improvement. These results validate the "gradient - free zone" concept underlying the new laser architecture.

Tests of the EAG composite-sample laser were performed with a cavity length of 27 mm and no intracavity mode-control aperture. Beam-quality (M^2) measurements at 300 mW average laser output with a pyroelectric-array camera gave $M_h^2 \approx 1.17$ in the horizontal direction and in the vertical dimension, $M_v^2 \approx 1.44$ was derived. Clearly, even with a short cavity, operation at $(M_h^2 \cdot M_v^2)^{1/2} \sim 1.3$ times diffraction limited is possible for this design. Compared with the original design delivering $P_{\text{out}} = 710 \, \text{mW}$ at $M_h^2 \approx 3.4$, $M_v^2 \approx 1.4$, with a 40 mm cavity length, the "effective far - field brightness," proportional to $P_{\text{out}}/(M_h^2 \cdot M_v^2)$, is comparable. While beam profiles from the composite laser look nearly gaussian, the original laser design shows spikes, particularly in the horizontal plane (where the lensing is worse.) Although multimode operation cannot be directly blamed on an intracavity lens, it is likely that

the original design exhibited higher-order thermal aberrations as well, which would affect beam quality more directly.

Slope-efficiency measurements (Figure 3) using the Er:YAG crystal with a pulsewidth and repetition rate of 500 μ sec and 120 Hz resulted in a threshold pump power of 1.3 Watt and a maximum average output power of 1.16 Watt. The maximum optical efficiency was 16%, roughly a factor of 2 better than that obtained with the original design. The 20% slope along the nearly-straight mid-portion of the slope-efficiency curve was also an improvement. Further laser performance increases should be obtainable by optimizing the Er concentration, improving the transmission of the pump light, and testing other crystalline host materials with higher luminescence quantum yields.

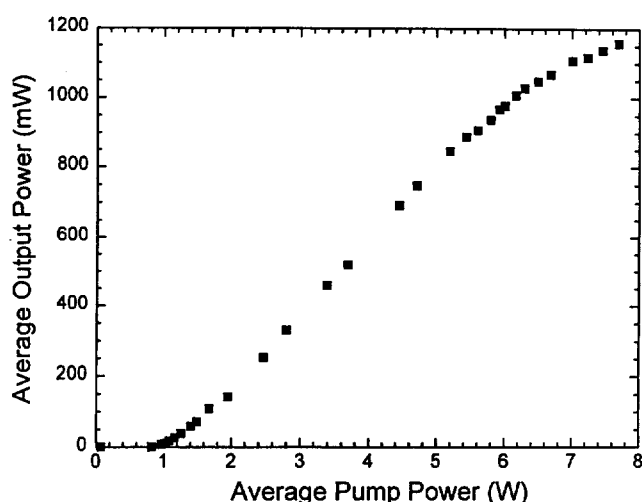


Figure 3. Input-output plot for the composite-sample Er:YAG laser operating with 500 μ sec drive pulses at 500 Hz, for a duty factor of 6%. The maximum optical and slope efficiencies are respectively 16% and 20%.

The new side-pumped, diffusion-bonded laser architecture allows efficient heat removal without flowing cooling water or gas across a crystal face. Its gradient-free region for resonated beam entry and exit provides a degree of thermal-lens compensation reminiscent of a highly-symmetric zig-zag slab system. This advanced sample geometry may be useful in other types of solid-state lasers where the gain is sensitive to operating temperature, or where thermal lensing is especially troublesome.

References

[1] R. C. Stoneman and L. Esterowitz, "Efficient resonantly pumped 2.8- μ m Er³⁺:GSGG laser," *Opt. Lett.* **17**, 816 (1992).

[2] M. Pollnau, W. Lüthy, H. P. Weber, T. Jensen, G. Huber, A. Cassanho, H. P. Jensen, and R. A. McFarlane, "Investigation of diode-pumped 2.8- μ m laser performance in Er:BaY₂F₈," *Opt. Lett.* **21**, 48 (1996).

[3] T. Jensen, B. G. Ostroumov, and G. Huber, "Upconversion processes in Er³⁺:YSGG and diode-pumped laser experiments at 2.8 μ m," in *OSA Proceedings on Advanced Solid-State Lasers*, Vol. **24**, Bruce H. T. Chai and Steven A. Payne (eds.), 1995, pp. 366 - 370.

[4] V. Lupei, S. Georgescu, and V. Florea, "On the dynamics of population inversion for 3 μ m Er³⁺ lasers," *IEEE J. Quantum Electron.* **29**, 426 (1993); M. Pollnau, Th. Graf, J. E. Balmer, W. Lüthy, and H. P. Weber, "Explanation of the cw operation of the Er³⁺ 3- μ m crystal laser," *Phys. Rev. A* **49**, 3990 (1994).

[5] B. J. Dinerman and P. F. Moulton, "3- μ m cw laser operations in erbium-doped YSGG, GGG, and YAG," *Opt. Lett.* **19**, 1143 (1994).

[6] T. Jensen, A. Diening, G. Huber, and B. Chai, "A diode pumped 1.1 W cw Er:YLF laser at 2.8 μ m," in *Conference on Lasers and Electro-Optics, OSA Technical Digest Series Vol. 15*, postdeadline paper CPD29 (1995).

[7] C. E. Hamilton, R. J. Beach, S. B. Sutton, L. H. Furu, and W. F. Krupke, "1-W average power levels and tunability from a diode-pumped 2.94- μ m Er:YAG oscillator," *Opt. Lett.* **19**, 1627 (1994).

[8] J. E. Bernard and A. J. Alcock, "High - efficiency diode - pumped Nd:YVO₄ slab laser," *Opt. Lett.* **18**, 968 (1993).

[9] Scientific Materials Corp., 310 Icepond Rd. P. O. Box 786, Bozeman MT 59715.

[10] ONYX Optics, 6545 Sierra Lane, Dublin CA 94568.

This work was performed under the auspices of the U.S.DOE by LLNL under contract no. W-7405-Eng-48.